Fire severity is more sensitive to low fuel moisture content on *Calluna* heathlands than on peat bogs

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Abstract

Moorland habitats dominated by the dwarf shrub *Calluna vulgaris* provide important ecosystem services. Drought is projected to intensify throughout their range, potentially leading to increased fire severity as moisture is a key control on severity. We studied the effect of low fuel moisture content (FMC) on fire severity by using 2 × 2 m rain-out shelters prior to completing 19 experimental fires in two sites in Scotland (UK): a dry heath with thin organic soils and a raised bog with deep, saturated peat, both dominated by *Calluna vulgaris*. Reduced FMC of the moss and litter (M/L) layer at both sites, and the soil moisture of the dry heath, increased fire-induced consumption of the M/L layer and soil heating at both sites. Increase in fire severity was greater at the dry heath than at the raised bog, e.g. average maximum temperatures at the soil surface increased from 31 °C to 189 °C at the dry heath, but only from 10 °C to 15 °C at the raised bog. Substantial M/L layer consumption was observed when its FMC was below 150 %. This led to larger seasonal and daily soil temperature fluctuation, particularly at the dry heath during warm months. The results suggest that low FMC following predicted changes in climate are likely to increase wildfire severity and that the impact on vegetation composition and

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carbon stores may be greater at heathlands than at peatlands. Managed burning aiming to minimise fire severity (e.g. ignition of the M/L layer and exposure to lethal temperatures of ericoid seeds) should be carried out when the FMC of the M/L layer is above 150 % and the FMC of the soil is above 200–300 %.

Keywords: wildfire, prescribed burning, moorland, fire temperature, soil microclimate, drought

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1. Introduction

Global warming during the 21st century is projected to increase water deficit in most regions, including northern Europe (Dai, 2013; Cook et al., 2014). For example, mean summer temperature in the United Kingdom (UK) is projected to increase by 2.5 °C, and rainfall to decrease by 16 % by 2050 (Murphy et al., 2009). Increased drought has the potential to substantially change wildfire activity (Krawchuk et al., 2009; Littell et al., 2016) through increased fire frequency (Albertson et al., 2010), severity (Turetsky et al., 2011b; Davies et al., 2013) and burnt area (Turetsky et al., 2004; Legg et al., 2007; Fernandes et al., 2016), and altered seasonality (Westerling et al., 2006).

In North-West Europe, vegetation communities dominated by the dwarf shrub *Calluna vulgaris* (L.) Hull (hereafter *Calluna*), including dry heaths on thin podzols and wet heaths on blanket and raised bogs (Gimingham, 1960), can be subjected to wildfires (Legg et al., 2007). In the UK, managed burning is used to improve habitat for game (mainly red grouse *Lagopus lagopus scoticus* Latham) and grazing for sheep and cattle (Allen et al., 2016) in many upland regions (Douglas et al., 2015). An altered fire regime resulting in part from intensified summer drought (Albertson et al., 2010; Davies and Legg, 2016) could jeopardise important ecosystem services provided by *Calluna* heathlands and peatlands; for instance cultural and recreation value (Thompson et al., 1995), regulation of water provision (Holden and Burt, 2003) and belowground carbon stocks (Bradley et al., 2005; Ostle et al., 2009). In particular, increased fire severity (defined *sensu* Keeley, 2009 as direct fire effects such as degradation or consumption of organic matter) can alter vegetation community composition and increase soil carbon losses. Direct mechanisms include higher thermal shock and ignition of belowground plant structures and organic soil layers (Clement and Touffet, 1990; Legg et al., 1992; Schimmel and Granström, 1996; Davies et al., 2013), and indirect, changes in post-fire ground fuel structure and microclimate (Maltby et al., 1990; Kettridge et al., 2012; Brown et al., 2015; Kettridge et al., 2015). Given the potential impacts of climate change on peatland fire regimes, quantitative information on how low fuel moisture content (FMC) may alter fire severity is urgently needed.

The moisture content of the different *Calluna* fuel layers is key in controlling fire behaviour (Davies and Legg, 2011). Low FMC of the live *Calluna* canopy has been found to increase fire rate of spread and fireline intensity, and low moisture content of dead elevated fuels to increase fire ignition potential (Davies et al., 2009). Low FMC of the moss and litter (M/L) layer leads to increased fuel consumption and to higher fire severity (Davies et al., 2010; Santana and Marrs, 2014; Davies et al., 2016a). In peatlands, drought can result in higher fire severity and full or partial consumption of the peat mass itself (Turetsky et al., 2011a; Davies et al., 2013). Important FMC thresholds have been identified at 60–70 % (dry base) for dead elevated fuels (Davies and Legg, 2011), above which field ignitions in small plots were difficult; 70–140 % for consumption of the M/L layer (Davies and Legg, 2011; Santana and Marrs, 2014); and 125–150 % for self-sustaining combustion of peat (Rein et al., 2008; Prat-Guitart et al., 2016). Nevertheless, previous research suggests that there are complex, non-linear relationships between FMC, fire behaviour and fire severity (Davies and Legg, 2011; Davies et al., 2016a; Fernandes et al., 2016).

Despite the crucial role of the moisture content of the different fuel layers of *Calluna* moorlands in controlling fire behaviour, its response to drought and subsequent effects on fire severity are not well understood (Legg et al., 2007; Flannigan et al., 2009). Quantifying the relationship between drought, FMC and fire severity is important for forecasting periods of potentially severe wildfires, predicting long-term changes in fire regimes due to climate change and advising on appropriate conditions for managed burning (Davies and Legg, 2016). Our broad aim here was thus to understand the role of low FMC in controlling fire severity and post-fire soil thermal dynamics in two *Calluna*-dominated sites with contrasting edaphic characteristics: (i) an upland dry heath with thin organic soils; and (ii) a lowland raised bog with deep, saturated peat. Our specific objectives were to contrast effects of low FMC between *Calluna*-dominated heathland and peatland to quantify:

1. The effect of low FMC on fire severity and its importance relative to other environmental variables such as fuel structure and wind speed.
2. The effect of variation in fire severity on post-fire soil thermal dynamics.

2. Materials and methods

2.1. Experimental design and measurements

The experiments were completed at two sites with similar above-ground fuel structure (> 85 % cover of mature *Calluna*, > 63 % cover of pleurocarpous mosses), but contrasting edaphic characteristics. Glen Tanar (elevation 460 m, latitude 57.016°N, longitude 2.974°W) is a dry heath with thin peaty podzols (mean depth of the organic horizon was 9 cm), whilst Braehead Moss (elevation 270 m, latitude 55.740°N, longitude 3.658°W) is a raised bog with deep (> 1.5 m) peat. 1981–2010 records from nearby weather stations (Aboyne, 13 km east of Glen Tanar, elevation 130 m, and Drumalbin, 13 km south of Braehead Moss, elevation 200 m; Met Office, 2010) show lower annual rainfall in Glen Tanar (780 mm) than in Braehead Moss (900 mm) but similar average air temperatures, both in summer (13.5 °C and 13.2 °C, respectively) and winter (2.6 °C and 2.8 °C, respectively).

A total of 19 experimental fires, each covering an area of ca. 25 × 30 m and burnt as head fires, were completed at Glen Tanar (10 fires) and Braehead Moss (9 fires) on twelve days between September 2013 and November 2014. 2 × 2 m rain-out shelters (Yahdjian and Sala, 2002), deployed two to four months before the experimental fires, and removed immediately before ignition, were used to simulate drought. Two plots under rain-out shelters ("drought" plots) and two untreated ("no-drought") plots were delimited in each fire. The rain-out shelters were made of a steel frame (height of the high side was 1.2 m, the low side was 0.5 m) and a clear polythene cover (thickness 250 μm, light transmittance 86 %; see Figure S1 in Supplementary Material). A gutter collected the rainfall, which was drained to a minimum distance of 5 m away through a hose. The rain-out shelters were oriented with the slope facing the direction of the prevailing wind to minimise the drift of precipitation. No ground structures were installed to regulate overland flow or lateral movement of water within the soil profile.

Fuel load and structure were estimated using the non-destructive FuelRule method, based on visual obstruction of a banded measurement stick (Davies et al., 2008), taking five measurements per plot (calibration of the method for our sites is detailed in Table S1 and Figure S2). Immediately before each fire we took a composite sample (three subsamples) of the top 2 cm of the M/L layer in each plot to estimate FMC. The samples were dried in a fan-assisted oven at 80 °C for at least 48 h, and FMC estimated on a dry weight basis. For both live and dead *Calluna* we took a composite FMC sample for each treatment within a fire, i.e. the samples were composited across the two plots of each treatment within each fire. Three soil moisture meter measurements in each plot were averaged to estimate the moisture content of the top 3.6 cm of the soil (here we use "soil" to refer both to the organic layer at Glen Tanar and peat at Braehead Moss). Soil moisture content measurements were taken with a FieldScout TDR 100 soil moisture meter (Spectrum Technologies, Inc.; see Table S2 and Figure S3 for calibration details). A portable weather station (Kestrel 4000) recorded air temperature, relative humidity and wind speed during the fires.

Hobo^{TM} loggers (Onset Computer Corporation) connected to K-type twisted pair thermocouples (multi-stranded leads of 0.2 mm of diameter) measured soil heating during the fires. Two loggers were buried in a central location in each experimental plot, with one thermocouple located at the soil surface (i.e. below the M/L layer) and one 2 cm below the base of the M/L layer (Figure 1). The thickness of the M/L layer above the top thermocouple was recorded to the nearest 0.5 cm.

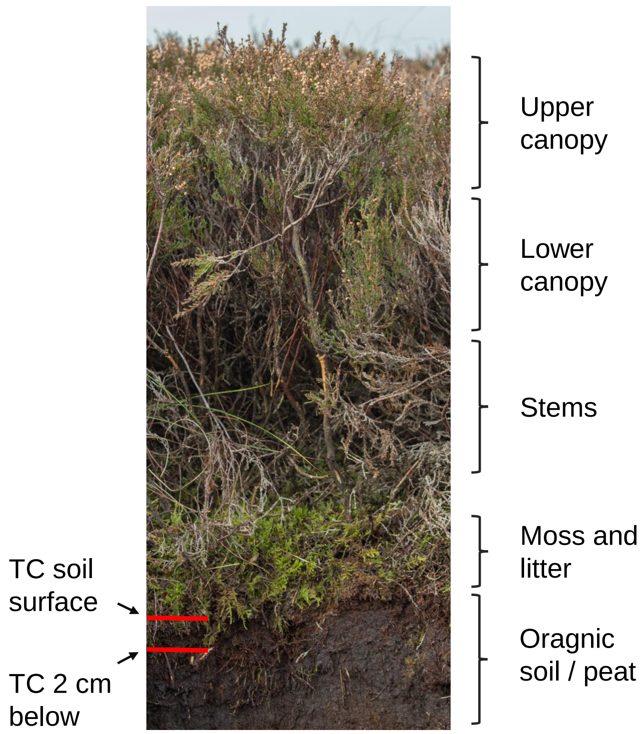

Figure 1: Location of the thermocouples (TC) at the soil surface and 2 cm below, in relation to a *Calluna* stand comprised of an upper live canopy, a lower canopy with a higher proportion of dead foliage, a lower layer of dead and live stems without foliage and a M/L layer on top of the soil.

We used five metal "duff spikes" (Brown et al., 1991) to mark the pre-fire position of the M/L layer surface in each plot, and assessed the extent of consumption of the M/L layer during the fire by measuring its change in depth to the nearest 1 cm. Temperature loggers (iButtons$^{\mathrm{TM}}$, 2 h measurement interval) installed 2 cm below the top of the soil recorded post-fire soil temperatures in five fires at Glen Tanar and in seven fires at Braehead Moss, from November 2014 to September 2015. For each fire we deployed an iButton logger in a randomly selected plot of each treatment (no-drought and drought) and in an unburnt control, and measured the thickness of the M/L layer above the logger to the nearest 0.5 cm. The exact location of the logger was chosen to best reflect average M/L layer thickness within each plot. We assessed post-fire soil accumulated heat by calculating the daily growing degree hours for each plot, i.e. the sum of °C above 4 °C, the minimum temperature for plant growth, in each hour during a day (Schenker et al., 2014).

2.2. Data analysis

Fire behaviour within a single fire varies widely due to changes in microtopography, heterogeneity in fuel density, fuel gaps and variation in wind speed (Bradstock and Auld, 1995; Bova and Dickinson, 2008; Davies et al., 2010). We therefore followed Fernandes et al.'s (2000) microplot approach for fire behaviour measurements and considered plots within fires as independent observations with regards to data analysis. The validity of the microplot approach was supported by the variance partitioning of fuel characteristics (e.g. canopy height, fuel load, bulk density, M/L layer thickness) showing larger or similar variation within fires compared to between fires at the same site (Table S3).

2.2.1. Effect of simulated drought on FMC

We examined the effect of the rain-out shelters on the FMC of the different *Calluna* fuel layers (live and dead canopy, M/L layer and soil) using separate linear mixed effects models (Table 1) to test (i) differences in FMC between treatments, within the same site, and (ii) differences in FMC between sites, within the same treatment. Multiple comparisons were addressed with simultaneous tests for general linear hypothesis (Hothorn et al., 2008).

2.2.2. Effect of low FMC on fire severity

Temperature-time curves recorded in each plot and measurement depth were characterised using three metrics: total heat (area under the curve; Equation 1), maximum temperature and time above 50 °C (a temperature threshold related to the potential for damage to plant tissue, seeds and soil microorganisms; Granström and Schimmel, 1993; Neary et al., 1999).

Table 1: Linear mixed effects models (Pinheiro et al., 2015) based on a two-way interaction as a fixed effect. Explanatory variables were site (Braehead Moss and Glen Tanar), treatment (U, unburnt; ND, no-drought; D, drought) and season (winter: December–February; spring: March–May; summer: June–August; autumn: September–November). Fire-induced soil heating metrics (maximum temperature and total heat) were log-transformed, and separate models fitted at the soil surface and 2 cm below. For GDH, separate models were fitted for each site. All models included fire as a random effect.

Model(s)	Response variable(s)	Fixed effects
Fuel moisture content (FMC)	Live *Calluna* FMC, dead *Calluna* FMC, M/L layer FMC, soil FMC	Site × treatment (ND, D)
Fire severity	M/L consumption, maximum soil T, total heat	Site × treatment (ND, D)
Growing degree hours (GDH)	GDH	Season × treatment (U, ND, D)

$$Total\ heat\ (^\circ C min) = \sum_{i=1}^{3000} (T_i - T_0) \times t_{interval}/60 \qquad (1)$$

where T_i is the soil temperature at i seconds after the start of the fire and T_0 is the temperature before the start of the fire. i ranged from 1 s (start of the fire) to 3000 s (50 min) after in increments of 5 s (measurement interval, $t_{interval}$). The 50 min limit captured most of the fire-induced heating as shown by temperature-time curves (examples are provided in Figures S8 and S9 in Supplementary Material).

Linear mixed effects models were used to test differences in fire severity (as estimated by M/L layer consumption and soil heating metrics) between no-drought and drought plots (Table 1). A high abundance of zeros in the time $> 50^\circ$C variable meant robust statistical testing was not possible, and analysis was based on summary statistics. We performed multiple comparisons to test differences in fire severity metrics between treatments, within the same site (and depth of measurement in the case of soil heating metrics), and (ii) between sites, within the same treatment.

2.2.3. Environmental controls on fire severity

We assessed the relative importance of FMC in controlling fire severity relative to other environmental variables by modelling fire severity as a function of weather and pre-fire fuel structure and moisture content variables. We used two different metrics of fire severity: consumption of the M/L layer and fire-induced soil heating as estimated by total heat. The available environmental covariates were wind speed, fuel load, thickness of the M/L layer, and FMC of live and dead *Calluna*, the M/L layer and soil. Available factor variables included site and depth of soil temperature measurement (only used for analysing soil heating). The total heat and moss consumption response variables were log-transformed. Given the multicollinearity (variance inflation factor > 3; Zuur et al., 2010) between the FMC of soil, live *Calluna* and dead *Calluna*, only the more relevant soil FMC (Busse et al., 2010) was retained in the models. The Akaike Information Criterion (AIC) was used for model selection. Variables were sequentially dropped until AIC did not increase by more than two units (Symonds and Moussalli, 2010) and all variables were significant ($\alpha = 0.05$).

2.2.4. Effect of low FMC on post-fire soil thermal dynamics

For each plot and day of measurement we calculated the daily mean temperature and the temperature range. Post-fire soil thermal dynamics were investigated using harmonic regression (Piegorsch and Bailer, 2005; Grau-Andrés et al., 2017). Separate models were fitted for each temperature metric (mean daily temperature and daily range) and site (Glen Tanar and Braehead Moss). The models included an interaction between the harmonic expression, M/L layer thickness and a factor variable ("Burnt") indicating whether the plot was burnt or unburnt as fixed effects (Equation 2), fire as a random effect and an autocorrelation structure of first order to account for the temporal dependence of the measurements (function "corAR1" in *nlme*; Pinheiro et al., 2015).

$$MDT/DTR_i = (cos(2\pi i/p) + \ sin(2\pi i/p)) \times ML_{thickness} \times Burnt \qquad (2)$$

where MDT/DTR_i is the estimated temperature metric (either Mean Daily Temperature or Daily Temperature Range) at sampling day i (1, 25 April 2013, to 350, 10 April 2014) within each site and p is the period of the sinusoid (365 days). We used linear mixed effects models and multiple comparison procedures to analyse the effect of treatment on growing degree hours within each site and season (Table 1).

3. Results

The experimental fires covered a range of weather conditions, e.g. average wind speed 2.2–7.5 m s^{-1} and pre-fire moisture content of the M/L layer in untreated plots 28–646 %. Fire rate of spread ranged 4.5–15.0 m min^{-1} as estimated by Davies et al.'s (2009) empirical equation for *Calluna* moorlands. The *Calluna* canopy was denser at Glen Tanar (mean ± standard deviation of fuel load above ground was 1.7 ± 0.1 kg m^{-2}) than at Braehead Moss (1.4 ± 0.1 kg m^{-2}), whilst the M/L layer was thinner at Glen Tanar (3.7 ± 0.8 cm) than at Braehead Moss (10.7 ± 3.7 cm). A summary of pre-fire fuel moisture and structure, as well as images of the experimental fires and of post-fire ground conditions, are provided in the Supplementary Material (Table S4 and Figure S4 to Figure S7).

3.1. *Effect of drought on FMC*

The drought treatment significantly lowered the FMC of the M/L layer, both at Glen Tanar (271 to 117 %) and at Braehead Moss (365 to 112 %). Soil FMC was only significantly altered at Glen Tanar (221 to 190 %) (Figure 2). Average soil FMC was significantly higher at Braehead Moss (349 %) than at Glen Tanar (205 %). Summary statistics of FMC of each fuel layer per treatment and site, and detailed statistical results can be found in the Supplementary Material (Tables S5–S7).

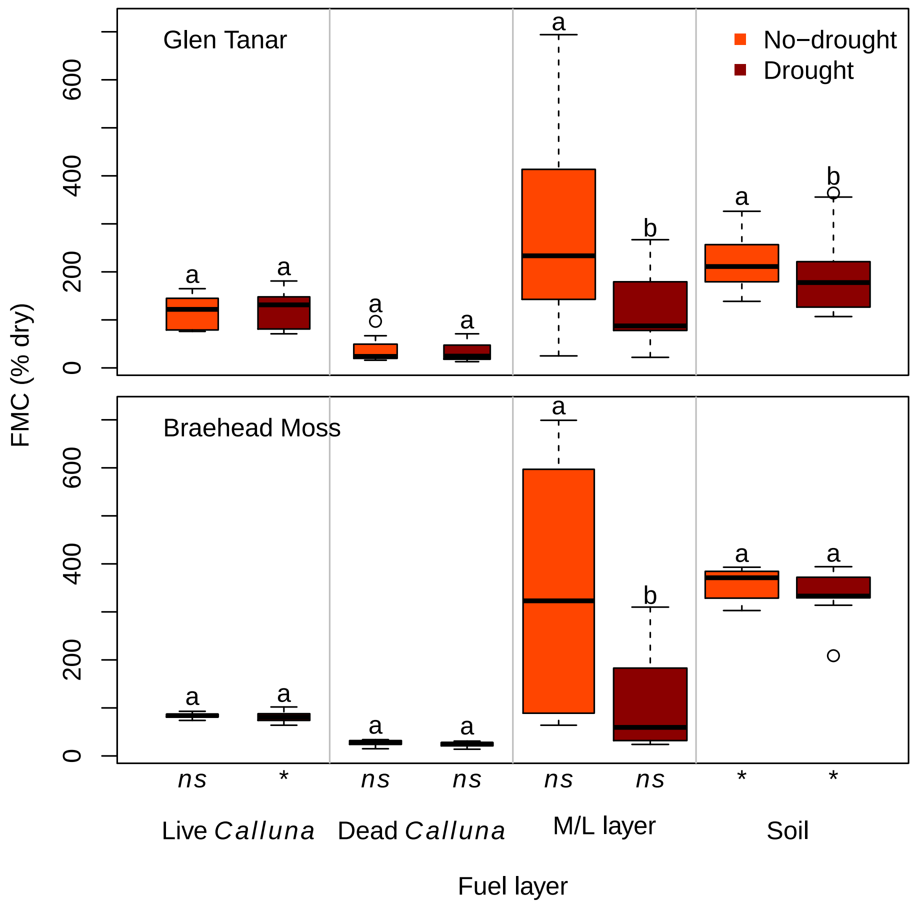

Figure 2: Pre-fire fuel moisture content of different fuel layers at Glen Tanar and Braehead Moss, in no-drought and drought plots. The box is the interquartile range and the thick horizontal line the median; whiskers extend to last datapoint within 1.5 times the interquartile range; circles are outliers beyond this range; width of the box is proportional to number of observations (max = 20, min = 7). Different letters above boxplots within the same site and fuel type indicate statistically significant differences. *ns* and * indicate significance of the FMC difference between sites, within the same fuel layer and treatment (*ns* = non-significant, * = statistically significant at $\alpha = 0.05$).

3.2. Effect of low FMC on fire severity

The drought treatment significantly increased fire severity as measured by M/L layer consumption, both at Glen Tanar (0.7 ± 1.1 cm in no-drought plots and 2.3 ± 1.7 cm in drought plots) and Braehead Moss (0.1 ± 0.3 cm in no-drought, 1.4 ± 1.1 cm in drought plots; see statistical testing details in Tables S8 and S9). There were no significant differences in M/L layer consumption between sites. The lower FMC in drought plots significantly increased total heat, at both depths of measurement, and at both sites (Table 2). Lower FMC increased average maximum temperatures at Glen Tanar, but not at Braehead Moss. Time above 50 °C was higher in drought compared to no-drought plots at Glen Tanar, but it was always zero at Braehead Moss. Fire-induced soil heating metrics were significantly higher at Glen Tanar than at Braehead Moss. Detailed results from the statistical analyses are provided in Tables S10 and S11 (Supplementary Material).

Table 2: Average values (standard deviation in parentheses) of metrics of fire-induced soil heating by depth of measurement (top of the soil and 2 cm below), treatment (no-drought and drought plots), and site (Glen Tanar and Braehead Moss). Different letters within temperature metric, depth of measurement and site indicate statistically significant differences between treatments ($\alpha = 0.05$).

Measurement depth	Soil surface		2 cm below	
Treatment	No-drought	Drought	No-drought	Drought
Site	Glen Tanar			
Total heat (°C min)	307 (241) a	1702 (2489) b	119 (104) a	674 (859) b
Max T (°C)	31 (24) a	189 (230) b	13 (6) a	40 (58) b
t above 50°C (s)	34 (88)	590 (919)	0 (0)	250 (610)
Site	Braehead Moss			
Total heat (°C min)	40 (62) a	146 (146) b	14 (16) a	46 (41) b
Max T (°C)	10 (3) a	15 (10) a	9 (1) a	10 (1) a
t above 50°C (s)	0 (0)	0 (0)	0 (0)	0 (0)

3.3. Environmental controls on fire severity

M/L layer consumption increased when it had lower pre-fire FMC (Figure 3). Most M/L layer consumption was observed when the M/L layer FMC was < 150 %, although consumption > 1 cm was observed up to 300 % FMC. The main drivers determining fire-induced soil heating in terms of total heat were the thickness and FMC of the M/L layer, the FMC of the soil and the depth of measurement (soil surface or 2 cm below) (Table 3). Modelled total heat increased substantially when soil moisture content decreased from ca. 300 to 200 %, and when the moisture content of the M/L layer was < 150 % (Figure 4).

Table 3: Details of the selected models for describing the fire severity indicators combustion of the M/L layer and soil heating. R^2 marginal is the variance explained by fixed effects and R^2 conditional is the variance explained by both fixed and random effects (Nakagawa and Schielzeth, 2013).

Response	R^2_m	R^2_c	Variable	Coefficient	DF	t-value	p-value
log(M/L consumed (cm))	0.57	0.71	Intercept	0.850	55	2.35	0.023
			M/L FMC (%)	-0.011	55	-10.07	<0.001
log(Total heat (°C min))	0.72	0.73	Intercept	9.610	123	27.93	<0.001
			TC depth (cm)	-0.950	123	-5.44	<0.001
			Soil FMC (%)	-0.011	123	-9.04	<0.001
			M/L FMC (%)	-0.004	123	-7.58	<0.001
			M/L thickness (cm)	-0.210	123	-6.25	<0.001

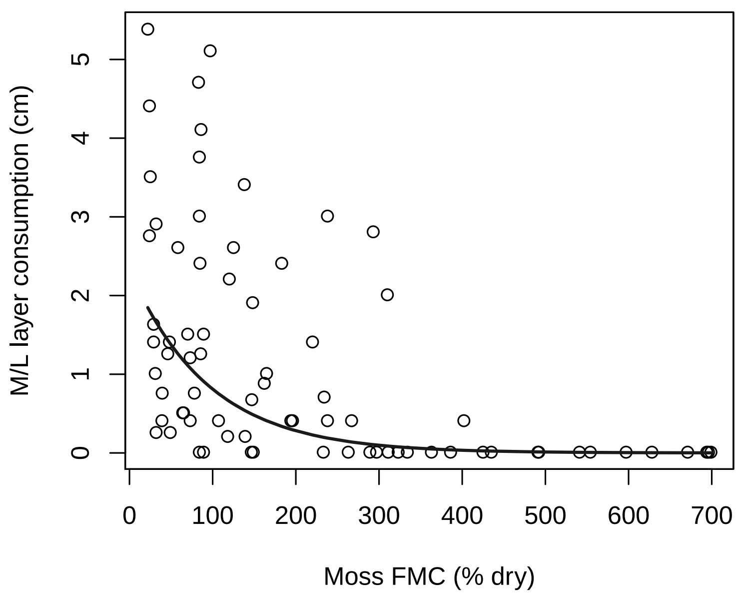

Figure 3: Observed (circles) and modelled (line) fire-induced consumption of the M/L layer as a function of pre-fire FMC of the M/L layer. See Table 3 for model details.

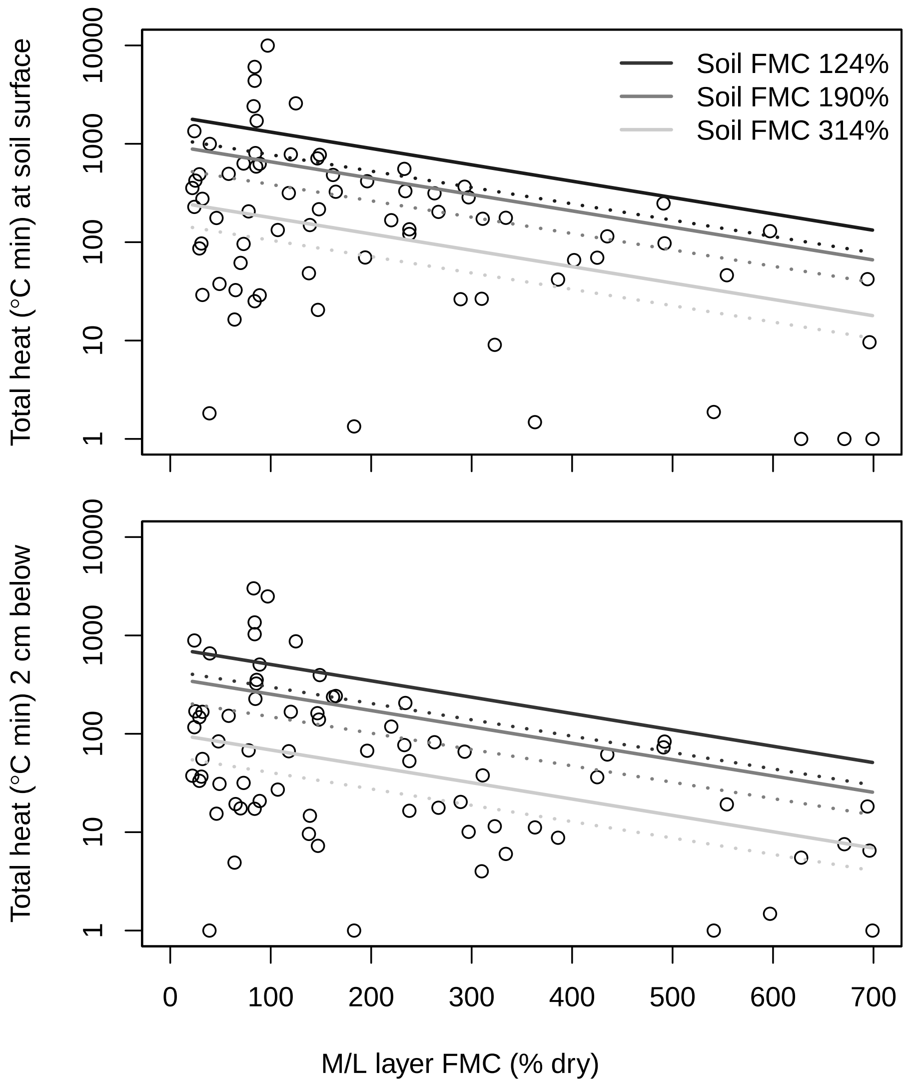

Figure 4: Total heat, measured at the soil surface (top) and 2 cm below (bottom) in relation to M/L layer FMC at both sites. Circles are observed values; lines are predicted values for 0.05, 0.25 and 0.5 quantiles of observed soil FMC (wetter soil led to very low soil heating) and for two M/L layer thicknesses: 0.25 quantiles of observed, in solid lines, and 0.75, in dottel lines. Model details are provided in Table 3. For reference, maximum temperatures at the soil surface > 50 °C occurred at total heat values > 450 °C min. Largest total heat values were associated with maximum temperatures up to 660 °C and 46 min > 50 °C.

3.4. Effect of low FMC on post-fire soil thermal dynamics

Mean daily temperature in burnt plots was higher than in unburnt plots during summer and lower during winter (i.e. annual extremes were higher) at both sites (Figure 5; see model details in Tables S14–S17). Furthermore, at Glen Tanar, burnt plots with thinner M/L layers were warmer than burnt plots with thicker M/L layers in summer (12.7 °C versus 11.9 °C) and colder in winter (0.6 °C versus 1.1 °C). Modelled post-fire daily soil temperature range was lowest in unburnt plots and highest in burnt plots with thin M/L layers. At Glen Tanar, daily temperature range had a strong dependence on season, with burnt plots with thin M/L layers having the largest daily temperature range, especially during the summer (9.4 °C), compared to burnt plots with thicker M/L layers (4.7 °C) and unburnt (2.2 °C). At Braehead Moss, daily temperature range was also larger in burnt plots (3.7 °C) than in unburnt (2.5 °C), but seasonal variation was small.

At Glen Tanar, accumulated soil heat as estimated by daily growing degree hours was higher in burnt than in unburnt plots (e.g. 86 versus 58 GDH in spring, 236 versus 191 in summer; Figure 6). Conversely, burning did not have an effect on soil accumulated heat at Braehead Moss.

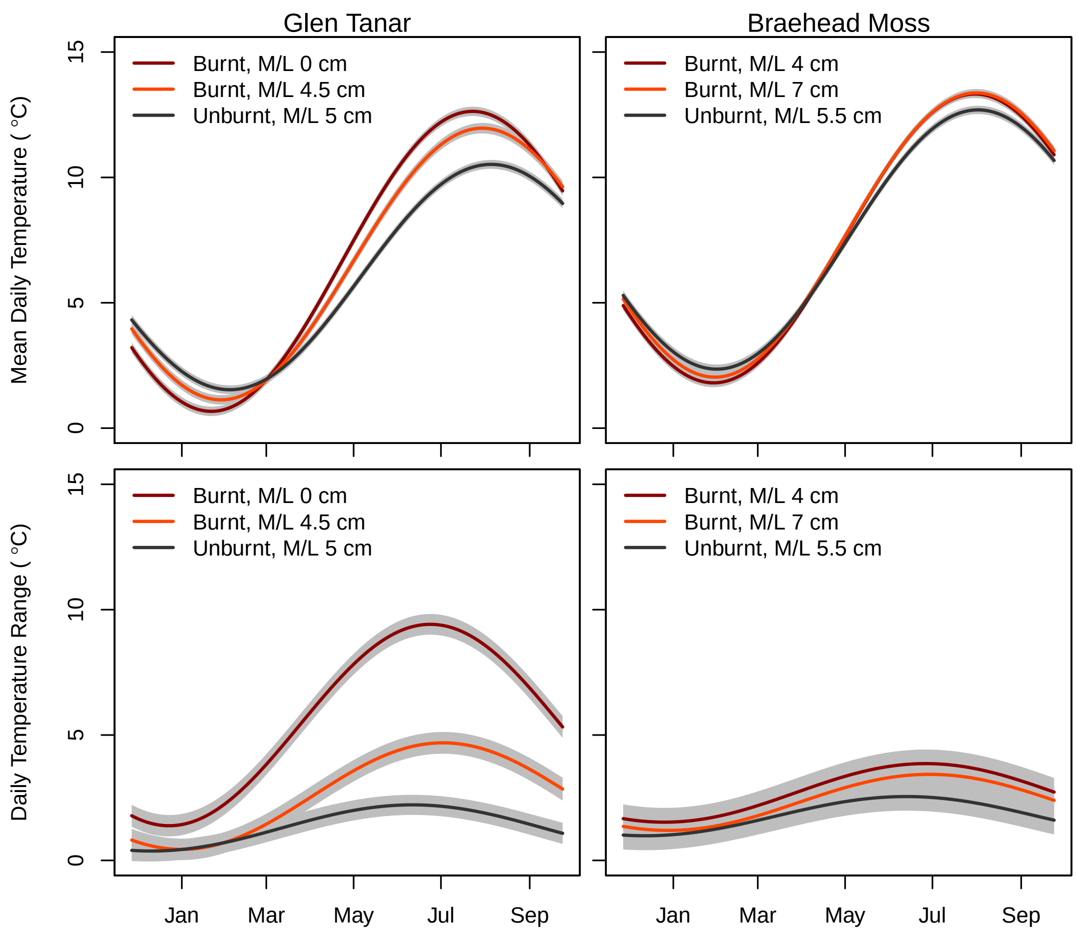

Figure 5: Modelled mean daily soil temperature and daily range 2 cm below the soil surface for 0.25 and 0.75 quantiles of post-fire M/L layer thickness in burnt plots, and average M/L layer thickness in unburnt, at both sites. Grey bands are 95 % confidence intervals.

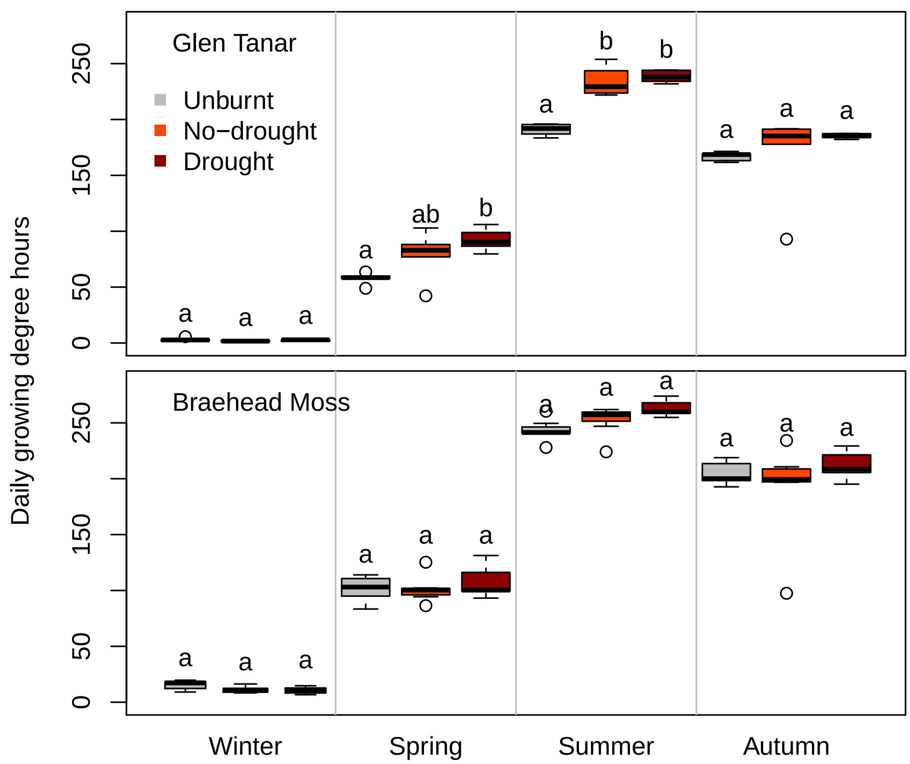

Figure 6: Post-fire soil accumulated heat as average daily growing degree hours for each site, season and treatment (unburnt, no-drought and drought plots). Width of the box is proportional to the number of observations (min = 4, max = 7). Different letters within site and season indicate significant differences between treatments ($\alpha = 0.05$). Full model results are provided in Tables S18–S21.

4. Discussion

4.1. Effect of simulated drought on fire severity

The simulated drought had the strongest effect on the FMC of the M/L layer (Figure 2). The rain-out shelters did not alter surface (upper 3.6 cm) soil moisture content at Braehead Moss, probably because raised bogs have a large capacity to store water, and this could have moved laterally (Waddington et al., 2015). The lower M/L layer FMC in drought plots (Figure 2) likely increased available fuel (i.e. *sensu* Alexander, 1982) resulting in greater consumption of the M/L layer. The contribution of the M/L layer to the total fuel load in *Calluna* moorlands can be substantial (13–67 % of total fuel load; Table S4) and so the flammability of the M/L layer has the potential to significantly alter fire behaviour (Davies et al., 2010, 2016a).

The drought treatment increased fire-induced soil heating, at both the soil surface and 2 cm below, and at both sites (Table 2). This increase in fire-induced soil heating was greater at the dry heath (Glen Tanar) than at the raised bog (Braehead Moss). For example, mean time above the ecologically critical 50 °C threshold at Glen Tanar increased from 34 s to almost 10 min at the soil surface and from 0 to 4 min 2 cm below the soil surface. Furthermore, mean maximum soil temperatures during burning at Glen Tanar increased by 158 °C at the soil surface and by 27 °C 2 cm below the soil surface (189 and 40 °C, respectively). These values are higher than those previously reported at 1 cm below the soil surface in *Calluna* heathland managed burning (30–70 °C; Hobbs and Gimingham, 1984) and suggest that burning under low FMC conditions could have important implications not just for vegetation regeneration in *Calluna* heathlands but also for soil microbial communities and soil physical and chemical characteristics (Ward et al., 2012). Drought can also alter post-fire substrates (lower moss cover and higher bare soil cover) and thus shape vegetation regeneration, e.g. *Calluna* seedlings establish better on soil than on M/L layers; Davies et al., 2010.

The higher total heat observed at the soil surface in drought plots compared to no-drought at Glen Tanar suggests that burning when FMC is low could facilitate the ignition of the organic soil layer (Hartford and Frandsen, 1992), and potentially lead to substantial carbon emissions (Davies et al., 2013) and ecological alteration of *Calluna* heathlands (Maltby et al., 1990). The lack of soil combustion in our experiments may be due to the high soil moisture contents (Figure 2) relative to the critical soil moisture content for self-sustained smouldering combustion (125–150 % for peat, Rein et al., 2008; Prat-Guitart et al., 2016).

The simulated drought had a much smaller effect on fire-induced soil heating at Braehead Moss: average maximum temperatures remained low (15 °C at the top of the soil and 10 °C 2 cm below) and far from temperatures that could negatively impact plant tissue, seeds or soil microorganisms (> 50 °C, Neary et al., 1999). This is likely due to the higher soil moisture content, which requires more energy per unit temperature increase (higher heat capacity) than dry soil (Abu-Hamdeh, 2003; Busse et al., 2010). In addition, at Braehead Moss, the higher insulation provided by the thicker M/L layer may have also played a role.

4.2. Environmental controls on fire severity

M/L layer consumption was primarily controlled by its pre-fire FMC (Table 3, Figure 3), while soil heating (as total heat) was also controlled by the thickness of the M/L layer and FMCs of the M/L layer and soil (Table 3, Figure 4). The negative relationship between the thickness of the M/L layer and fire-induced soil heating indicates the importance of the M/L layer in insulating soil from temperature pulses (Grau-Andrés, 2017; Grau-Andrés et al., 2017). Higher FMCs limit M/L combustion (Davies and Legg, 2011), while increased soil FMC reduces soil heating by increasing soil heat capacity and energy required for evaporation (Busse et al., 2005, 2010). Both when considering consumption of the M/L layer and fire-induced soil heating, the highest fire severity occurred when the FMC of the M/L layer was below ca. 150 %. This is a higher critical threshold than previously reported for substantial consumption of *Calluna* heathland M/L layers (70 %, Davies and Legg, 2011; 33–71 %, Santana and Marrs, 2014). The higher threshold seen here is probably due to the smaller size of the burns used in these previous studies (2 × 2 m plots in Davies and Legg, 2011; 25 cm diameter trays in Santana and Marrs, 2014), which is likely to have limited achievable fireline intensity.

4.3. Effect of low FMC on post-fire soil thermal dynamics

Burning increased seasonal and daily soil temperature ranges (Figure 5), as previous research has reported for UK *Calluna* moorlands (Brown et al., 2015; Grau-Andrés et al., 2017) and Canadian peat bogs (Kettridge et al., 2012). M/L layer consumption was a key control on altered post-fire soil thermal dynamics by decreasing the thickness of the M/L layer, therefore reducing its capacity to insulate soil temperatures from variation in air temperature and solar radiation. Fire-induced changes in latent heat fluxes (Kettridge et al., 2012) and ground surface albedo (López-Saldaña et al., 2015) could have also played a role. At Glen Tanar, the thinner M/L layer following increased combustion in drought plots led to larger seasonal and daily soil temperature fluctuations compared to burnt plots with thicker M/L layers. The thicker M/L layer and lower consumption of the M/L layer during burning at Braehead Moss may have contributed to the lower alteration to post-fire soil thermal dynamics in the raised bog compared to the dry heath.

However, given the much thicker and wetter soils at the raised bog compared to the dry heath, and the importance of water in regulating thermal dynamics due to its large thermal inertia (Busse et al., 2010), hydrological differences between the sites were probably key in explaining differences in post-fire soil thermal dynamics. This is supported by the fact that differences in post-fire soil thermal dynamics between both sites were larger for daily temperature range than for mean daily temperature. The influence of the large thermal inertia of water at Braehead Moss may have dampened shorter-term (daily) temperature fluctuation, rather than altering longer-term seasonal patterns, which may be more influenced by differences in climate between the sites (Zhuang et al., 2002).

The greater soil temperature range after fire could have an effect on post-fire vegetation regeneration by stimulating seed germination (Thompson and Grime, 1983) and by leading to higher soil accumulated heat during spring and summer (Figure 6). Warmer soils during the growing season could facilitate regeneration of recently-burnt plants with living parts entirely below ground. Warmer soils during summer could increase soil respiration and contribute to higher carbon losses in the years following burning (Dorrepaal et al., 2009).

5. Conclusions

Low FMC increased fire effects more strongly at the dry heath (Glen Tanar) than the raised bog (Braehead Moss) site. At the dry heath, low M/L layer and soil FMC resulted in significantly higher M/L layer consumption and soil heating. Increased M/L layer consumption altered post-fire soil thermal dynamics: burnt plots, especially those with a thinner M/L layer, showed wider daily and seasonal temperature fluctuations than unburnt plots. At the raised bog, fire-induced soil heating and alteration of post-fire soil thermal dynamics were very low compared to the dry heath. Increased consumption of the M/L layer and higher soil heating occurred when the moisture content of the M/L layer was below 150 %. Lower soil moisture content (below 200–300 %) also contributed to higher fire severity. The results suggest that fire severity in heathlands may be more sensitive to low FMC than bogs, and that, in a context of climate change where increased summer droughts are projected, *Calluna* heathlands community composition and carbon stores may be more at risk than peatlands. The low fire severity observed at the raised bog, even at low FMCs, suggest that assumptions and debates (Davies et al., 2016b) about the relative ecological resilience of bogs and heathlands to managed fire should be re-examined.

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6. Supplementary material

6.1. Drought shelters

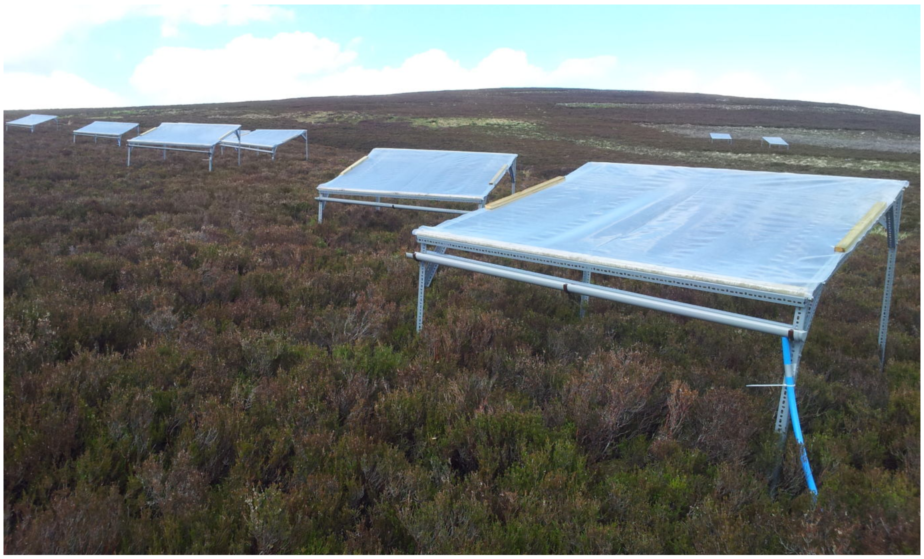

Figure S1: Rain-out shelters at Glen Tanar.

6.2. FuelRule calibration

Table S1: Details of the linear regression models used to calibrate fuel load (kg m^{-2} of dry weight) of *Calluna* fuel layers estimated using the FuelRule methodology (Davies et al., 2008) using destructive sampling. Fine fuel refers to live and dead stems < 2 mm in diameter and all foliage. Sampling was carried out in Kirkconnell Flow (southern Scotland, latitude 55.0156°N, longitude 3.618°W), a raised bog with areas around the margins with similar fuel structure as that found at Glen Tanar and Braehead Moss, i.e. mature *Calluna* cover above 85 % and a bryophyte layer dominated by pleurocarpous mosses. Nine FuelRule measurements were averaged in each plot. Fuel was separated by type in the laboratory, and dried at 80 °C until constant weight using a fan-assisted oven.

	Estimate	Std. Error	t value	p value	DF	R^2
Total fuel above moss						
Intercept	0.16	0.43	0.38	0.71	12	0.64
Slope	1.35	0.29	4.61	<0.001		
Fine fuel above moss						
Intercept	0.18	0.42	0.43	0.68	12	0.41
Slope	1.31	0.45	2.91	0.01		
Moss						
Intercept	0.67	0.09	7.08	<0.001	12	0.50
Slope	0.43	0.12	3.50	<0.001		
Moss and buried stems						
Intercept	0.94	0.14	6.81	<0.001	12	0.45
Slope	0.48	0.15	3.15	0.01		

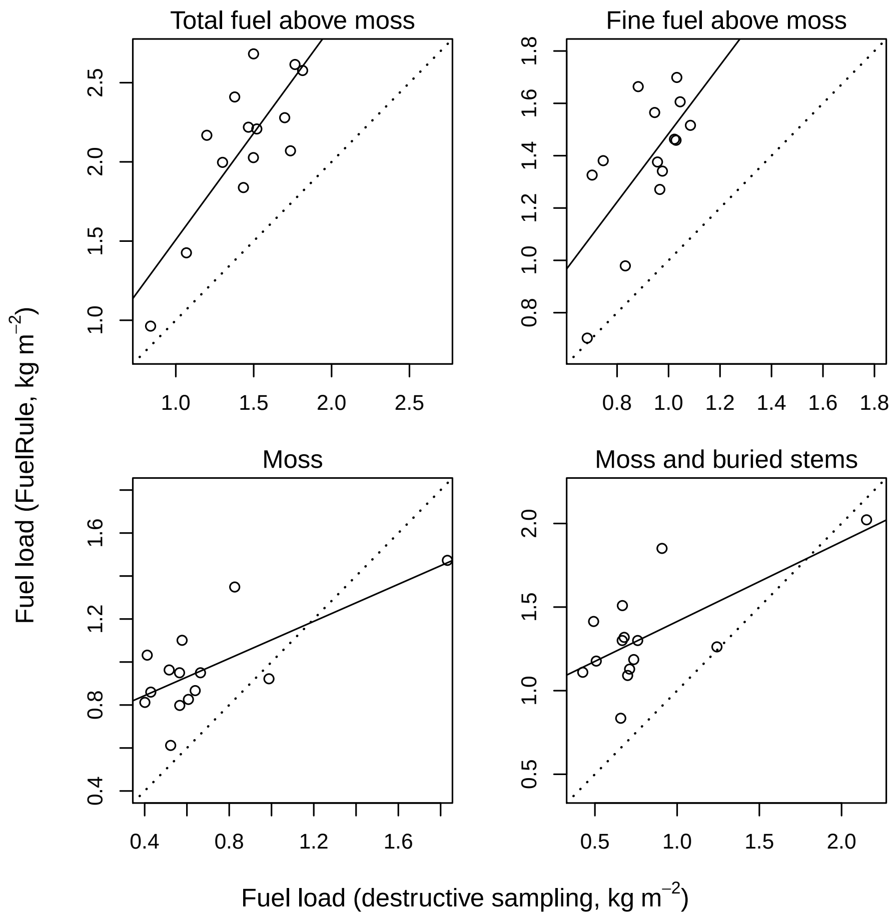

Figure S2: Relationship between fuel load of different *Calluna* fuel layers estimated using the FuelRule method and using destructive sampling. Dotted lines indicate perfect agreement and solid lines show fitted values following the models described in Table S1.

6.3. Soil moisture meter calibration

Table S2: Linear regression model relating permittance measurements from the soil moisture meter and soil fuel moisture content (in dry weight) calculated gravimetrically using a fan-assisted oven at 80 °C until constant weight.

	Estimate	Std. Error	t value	p value	DF	R^2
Intercept	-329.20	53.08	-6.20	<0.001	10	0.92
Slope	0.21	0.02	10.41	<0.001		

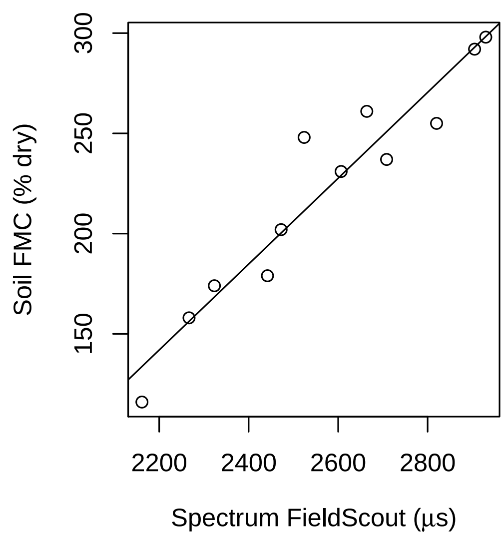

Figure S3: Relationship between soil moisture content in dry weight and the signal time travel measurement given by the soil moisture meter. The lines indicate fitted values following the model described in Table S2.

6.4. Variance partitioning of fuel characteristics

Table S3: Variance partitioning (function "lmer" in package *lme4*; Bates et al., 2015) of fuel characteristics in "between fire" and "within fire" variance at Glen Tanar and Braehead Moss, expressed as % of total variance.

	Glen Tanar		Braehead Moss	
	Between	Within	Between	Within
Total fuel (kg m^{-2})	11	89	37	63
Fine fuel (kg m^{-2})	6	94	38	62
Bulk density (kg m^{-3})	27	73	37	63
Height (m)	7	93	2	98
M/L thickness (cm)	0	100	10	90

Table S4: Summary of pre-fire fuel load and structure (estimated using the FuelRule method; Davies et al., 2008), pre-fire fuel moisture content in untreated plots, wind speed during the fires and fire rate of spread. Fire rate of spread was estimated using Davies et al.'s (2009) empirical equation for *Calluna* moorlands based on *Calluna* height and wind speed. Columns are date of burning, maximum height of the *Calluna* canopy, total biomass above moss, fine fuel biomass above moss, thickness of the M/L layer, M/L layer fuel load, FMC of upper live *Calluna* canopy, FMC of elevated dead *Calluna*, FMC of the M/L layer, wind speed and fire rate of spread.

Fire	Date	Height (m)	Total fuel (kg m^{-2})	Fine fuel (kg m^{-2})	M/L (cm)	M/L fuel (kg m^{-2})	*Calluna* (l) FMC	*Calluna* (d) FMC	M/L FMC	Wind (m s^{-2})	RoS (m min^{-1})
					Glen Tanar						
1	10/09/13	0.49	1.63	0.80	4.75	0.59	148	67	418	4.6	9.5
2	10/09/13	0.46	1.66	0.80	4.00	0.49	150	97	394	4.3	8.0
3	24/09/13	0.47	1.74	0.83	3.62	0.43			234	2.8	5.8
4	24/09/13	0.43	1.56	0.78	3.62	0.43			134	2.9	5.1
5	30/10/13	0.49	1.76	0.85	2.77	0.31	78	32	592	7.5	15.0
6	11/03/14	0.48	1.63	0.79	4.88	0.61	84	16	380	3.7	7.5
7	11/03/14	0.43	1.47	0.74	2.80	0.31	76	18	262	2.9	5.0
8	11/04/14	0.50	1.65	0.81	4.53	0.56	79	24	28	5.2	11.0
9	03/09/14	0.51	1.80	0.85	3.40	0.40	140	22	148	4.4	9.9
10	03/09/14	0.46	1.68	0.81	2.60	0.28	121	28	163	3.9	7.2
					Braehead Moss						
1	10/10/13	0.53	1.25	0.62	17.62	2.46	87		646	4.3	10.4
2	10/10/13	0.48	1.27	0.64	13.38	1.85	87	34	626	4.1	8.2
3	11/10/13	0.49	1.26	0.62	11.62	1.59	93	32	541	3.2	6.9
4	16/04/14	0.46	1.41	0.71	10.12	1.37	84	15	86	3.1	6.1
5	16/04/14	0.46	1.39	0.71	9.88	1.34	77	15	106	2.3	4.7
6	25/04/14	0.46	1.16	0.58	13.50	1.86	86	24	71	2.2	4.5
7	16/10/14	0.50	1.63	0.80	6.40	0.83	81	28	300	2.7	6.2
8	16/10/14	0.50	1.52	0.75	6.84	0.90	83	28	343	3.1	7.0
9	13/11/14	0.51	1.44	0.70	7.20	0.95	74	25	650	4.1	9.2

6.6. Images of the fires and post-fire fuel conditions

Figure S4: Example of an experimental fire at Glen Tanar.

Figure S5: Example of an experimental fire at Braehead Moss.

Figure S6: Detail of post-fire ground fuel conditions at Glen Tanar, with prolonged smouldering in a drought plot.

Figure S7: Ground fuels in drought plots at Braehead Moss smouldering ca. 5 min after the passage of the fire front.

6.7. Fire-induced soil heating temperature-time curves

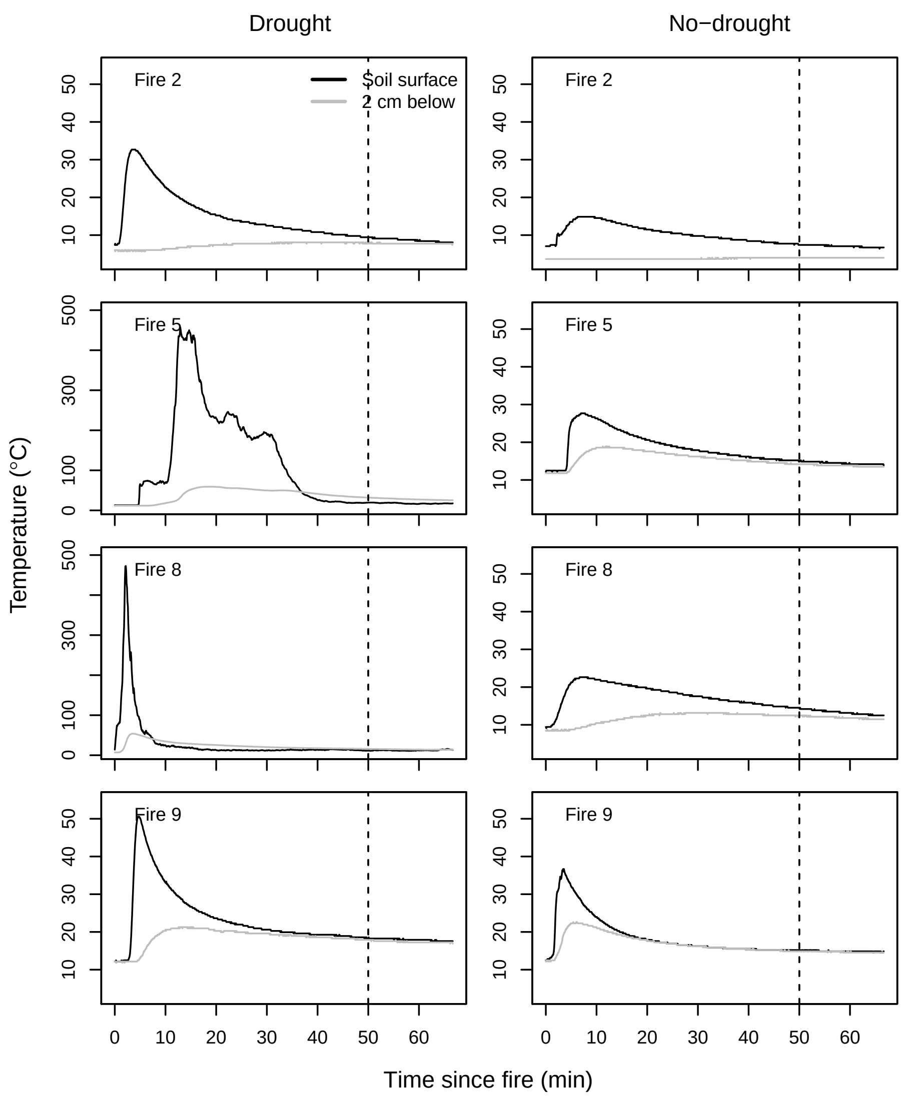

Figure S8: Examples of soil heating during experimental fires at Glen Tanar in drought plots (left) and no-drought plots (right). The dotted line at 50 minutes after the start of the fire indicate the cut point for calculating total heat.

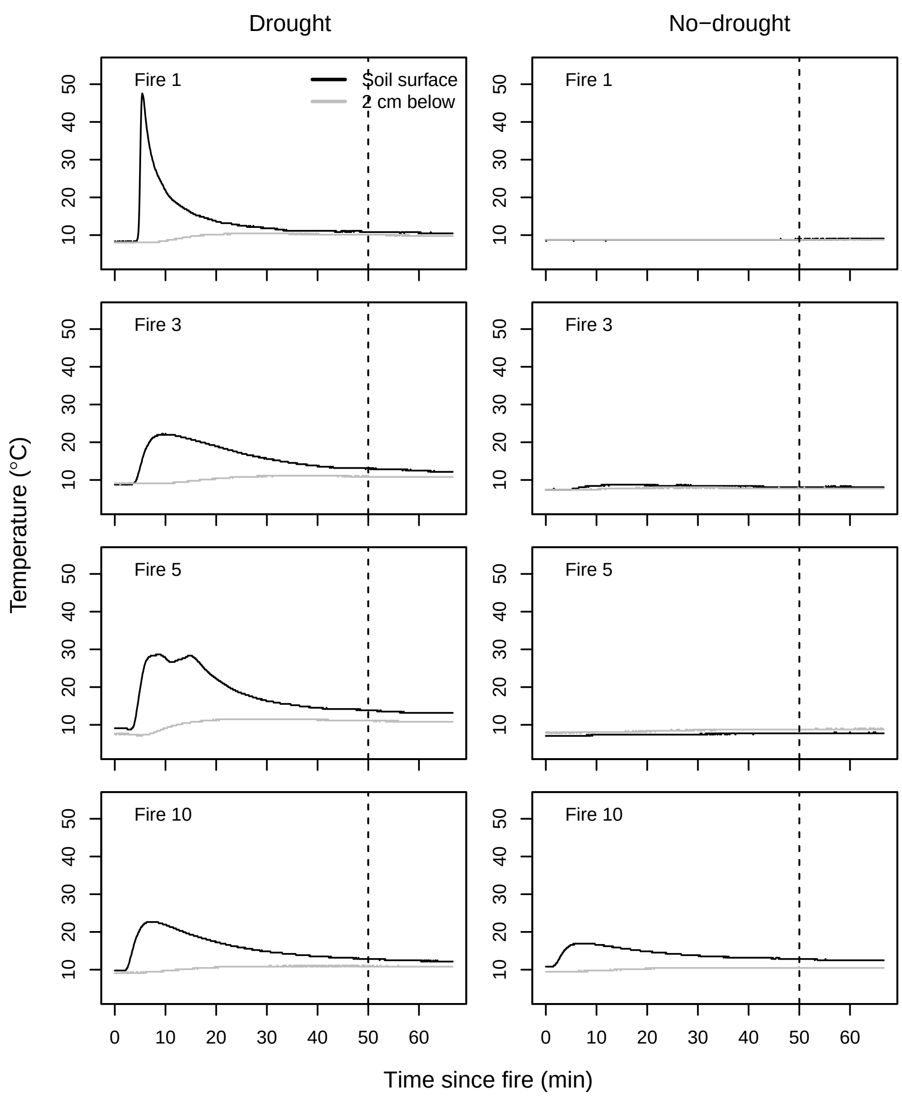

Figure S9: Examples of soil heating during experimental fires at Braehead Moss in drought plots (left) and no-drought plots (right). The dotted line at 50 minutes after the start of the fire indicate the cut point for calculating total heat.

6.8. Effect of drought on fuel moisture content

Table S5: Summary statistics of fuel moisture content for different sites, fuel layers and treatments.

Site	fuel	Treatment	Mean (SD)	Min	Max	n
GT	*Calluna* live	No-drought	117 (35)	76	165	10
		Drought	121 (38)	71	181	10
	Calluna dead	No-drought	39 (31)	16	97	7
		Drought	33 (22)	13	71	8
	M/L layer	No-drought	271 (180)	25	694	20
		Drought	117 (72)	22	267	20
	Soil	No-drought	221 (60)	139	326	20
		Drought	190 (79)	107	364	20
BM	*Calluna* live	No-drought	84 (6)	74	93	9
		Drought	82 (11)	64	102	9
	Calluna dead	No-drought	26 (7)	15	34	9
		Drought	23 (6)	14	31	9
	M/L layer	No-drought	365 (248)	64	699	17
		Drought	112 (101)	24	310	18
	Soil	No-drought	357 (30)	303	393	18
		Drought	341 (42)	209	394	18

Table S6: Details of linear mixed effects models investigating the effect of the interaction between site (Glen Tanar and Braehead Moss) and treatment ("Tr": no-drought or drought) on fuel moisture content in different fuel layers.

	Value	Std.Error	DF	t-value	p-value	R^2m	R^2c
			Calluna live				
Intercept	83.56	7.71	19	10.83	<0.001	0.29	0.96
Site(GT)	26.01	11.89	15	2.19	0.045		
Trt(Drought)	-1.78	2.59	19	-0.69	0.500		
Site(GT) : Tr(Drought)	5.83	6.54	19	0.89	0.384		
			Calluna dead				
Intercept	25.89	5.74	15	4.51	<0.001	0.11	0.98
Site(GT)	12.89	8.71	15	1.48	0.160		
Trt(Drought)	-2.44	1.31	14	-1.87	0.082		
Site(GT) : Tr(Drought)	-3.31	3.77	14	-0.88	0.395		
			Moss and litter layer				
Intercept	370.04	50.26	54	7.36	<0.001	0.29	0.68
Site(GT)	-98.55	67.74	17	-1.45	0.164		
Trt(Drought)	-258.21	38.22	54	-6.76	<0.001		
Site(GT) : Tr(Drought)	103.51	49.02	54	2.11	0.039		
			Soil				
Intercept	357.04	18.34	55	19.47	<0.001	0.62	0.93
Site(GT)	-136.45	25.36	17	-5.38	<0.001		
Trt(Drought)	-16.14	8.26	55	-1.95	0.056		
Site(GT) : Tr(Drought)	-14.23	11.75	55	-1.21	0.231		

Table S7: Multiple comparison tests examining differences in FMC in different fuel layers between levels of treatment (no-drought and drought) within the same site (Glen Tanar and Braehead Moss) and between sites within the same treatment. The linear mixed effects models tested the effect of the interaction between treatment and site on fuel moisture content of different fuel layers (see Table S6).

	Estimate	Std. Error	z value	p value
		Calluna live		
Drought vs No-drought in BM	-1.8	2.6	-0.69	0.880
Drought vs No-drought in GT	4.0	6.0	0.67	0.886
GT vs BM in Drought	26.0	11.9	2.19	0.096
GT vs BM in No-drought	31.8	11.9	2.68	0.026
		Calluna dead		
Drought vs No-drought in BM	-2.4	1.3	-1.87	0.189
Drought vs No-drought in GT	-5.8	3.5	-1.63	0.301
GT vs BM in Drought	12.9	8.7	1.48	0.385
GT vs BM in No-drought	9.6	8.6	1.11	0.627
		Moss and litter layer		
Drought vs No-drought in BM	-258.2	38.2	-6.76	<0.001
Drought vs No-drought in GT	-154.7	30.7	-5.04	<0.001
GT vs BM in Drought	-98.5	67.7	-1.45	0.409
GT vs BM in No-drought	5.0	67.4	0.07	1.000
		Soil		
Drought vs No-drought in BM	-16.1	8.3	-1.95	0.160
Drought vs No-drought in GT	-30.4	8.4	-3.63	<0.001
GT vs BM in Drought	-136.5	25.4	-5.38	<0.001
GT vs BM in No-drought	-150.7	25.4	-5.94	<0.001

6.9. Effect of drought on consumption of the moss and litter layer

Table S8: Details of the linear mixed effects model investigating differences in M/L layer consuption between sites (Glen Tanar and Braehead Moss), and treatments ("Tr": no-drought and drought). R^2 marginal was 0.50 and R^2 conditional, 0.97.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	2.306	0.388	55	5.95	<0.001
Site(BM)	-0.860	0.564	17	-1.53	0.145
Tr(No-drought)	-1.623	0.295	55	-5.50	<0.001
Site(BM) : Tr(No-drought)	0.311	0.429	55	0.72	0.472

Table S9: Multiple comparison tests examining differences in fire-induced M/L layer consumption between levels of treatment (no-drought or drought) within the same site (Glen Tanar or Braehead Moss) and between sites within the same treatment. See Table S8 for model details.

Comparison	Estimate	Std. Error	z-value	p-value
Drought vs No-drought in GT	-1.623	0.30	-5.50	<0.001
Drought vs No-drought in BM	-1.312	0.31	-4.21	<0.001
GT vs BM in Drought	-0.860	0.56	-1.53	0.361
GT vs BM in No-drought	-0.549	0.38	-1.47	0.397

6.10. Fire-induced soil heating

Table S10: Details of linear mixed effects models investigating the effect of the interaction between site (Glen Tanar and Braehead Moss) and treatment ("Tr": no-drought and drought) on different soil heating metrics, at the soil surface and 2 cm below.

	Value	Std.Error	DF	t-value	p-value	R^2m	R^2c
			log(Total heat (°C min)), 2 cm depth				
Intercept	5.48	0.38	51	14.50	<0.001	0.44	0.68
Site(BM)	-2.04	0.55	17	-3.74	0.002		
Tr(No-drought)	-1.25	0.34	51	-3.66	<0.001		
Site(BM) : Tr(No-drought)	-0.01	0.49	51	-0.01	0.989		
			log(Total heat (°C min)), soil surface				
Intercept	6.60	0.35	51	18.98	<0.001	0.59	0.76
Site(BM)	-1.83	0.52	17	-3.52	0.003		
Tr(No-drought)	-1.22	0.32	51	-3.85	<0.001		
Site(BM) : Tr(No-drought)	-1.25	0.48	51	-2.62	0.012		
			log(Maximum T (°C)), 2 cm depth				
Intercept	2.94	0.16	51	18.09	<0.001	0.35	0.90
Site(BM)	-0.65	0.23	17	-2.83	0.012		
Tr(No-drought)	-0.49	0.12	51	-4.18	<0.001		
Site(BM) : Tr(No-drought)	0.35	0.16	51	2.13	0.038		
			log(Maximum T (°C)), soil surface				
Intercept	4.24	0.27	54	15.48	<0.001	0.60	0.81
Site(BM)	-1.64	0.40	17	-4.08	<0.001		
Tr(No-drought)	-1.11	0.25	54	-4.38	<0.001		
Site(BM) : Tr(No-drought)	0.77	0.37	54	2.06	0.044		

Table S11: Multiple comparison tests examining differences in different temperature metrics at the soil surface or 2 cm below between levels of treatment (no-drought or drought) within the same site (Glen Tanar or Braehead Moss) and between sites within the same treatment. The linear mixed effects models tested the effect of the interaction between treatment and site on temperature metrics (see Table S10).

Comparison	Estimate	Std. Error	z-value	p-value
	log(Total heat (°C min)), 2 cm depth			
Drought vs No-drought in GT	-1.246	0.340	-3.663	<0.001
Drought vs No-drought in BM	-1.252	0.350	-3.581	0.001
GT vs BM in Drought	-2.043	0.546	-3.741	0.001
GT vs BM in No-drought	-2.050	0.539	-3.804	<0.001
	log(Total heat (°C min)), soil surface			
Drought vs No-drought in GT	-1.223	0.318	-3.847	<0.001
Drought vs No-drought in BM	-2.477	0.358	-6.915	<0.001
GT vs BM in Drought	-1.826	0.518	-3.523	0.002
GT vs BM in No-drought	-3.080	0.510	-6.045	<0.001
	log(Maximum T (°C)), 2 cm depth			
Drought vs No-drought in GT	-0.489	0.117	-4.181	<0.001
Drought vs No-drought in BM	-0.140	0.114	-1.232	0.549
GT vs BM in Drought	-0.654	0.231	-2.826	0.017
GT vs BM in No-drought	-0.305	0.179	-1.704	0.268
	log(Maximum T (°C)), soil surface			
Drought vs No-drought in GT	-1.109	0.253	-4.379	<0.001
Drought vs No-drought in BM	-0.339	0.274	-1.238	0.548
GT vs BM in Drought	-1.643	0.403	-4.081	<0.001
GT vs BM in No-drought	-0.874	0.250	-3.491	0.002

Table S12: Details of the linear mixed effects model investigating differences in post-fire M/L thickness above the soil temperature loggers between sites (Glen Tanar and Braehead Moss), and treatments (“Tr”: unburnt, no-drought and drought). A constant variance function was used for site. R^2 marginal was 0.29 and R^2 conditional, 0.44.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	4.900	0.683	20	7.17	$<$0.001
Site(BM)	0.743	1.245	10	0.60	0.564
Tr(No-drought)	-1.500	0.541	20	-2.77	0.012
Tr(Drought)	-3.900	0.541	20	-7.21	$<$0.001
Site(BM) : Tr(No-drought)	0.571	1.414	20	0.40	0.690
Site(BM) : Tr(Drought)	4.900	1.414	20	3.46	0.002

Table S13: Multiple comparisons of differences in post-fire thickness of the M/L layer above the soil temperature loggers between sites (Glen Tanar and Braehead Moss) and treatments (unburnt, no-drought and drought). See Table S12 for model details.

	Estimate	Std. Error	z-value	p-value
GT:nodrought - unburnt	-1.50	0.54	-2.77	0.03
GT:drought - unburnt	-3.90	0.54	-7.21	0.00
GT:drought - nodrought	-2.40	0.54	-4.44	0.00
BM:nodrought - unburnt	-0.93	1.31	-0.71	0.94
BM:drought - unburnt	1.00	1.31	0.77	0.92
BM:drought - nodrought	1.93	1.31	1.48	0.51

Table S14: Details of the daily temperature range harmonic model in Glen Tanar. R^2 marginal was 0.65 and R^2 conditional, 0.66.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	2.57	0.38	4356	6.74	<0.001
cos	-0.63	0.34	4356	-1.82	0.068
sin	0.43	0.31	4356	1.40	0.162
ML.cm	-0.25	0.07	4356	-3.78	<0.001
burntTRUE	2.83	0.31	4356	9.06	<0.001
cos:ML.cm	-0.05	0.07	4356	-0.77	0.442
sin:ML.cm	-0.13	0.06	4356	-2.15	0.032
cos:burntTRUE	-2.96	0.35	4356	-8.36	<0.001
sin:burntTRUE	-2.24	0.32	4356	-7.03	<0.001
ML.cm:burntTRUE	-0.38	0.06	4356	-6.36	<0.001
cos:ML.cm:burntTRUE	0.47	0.07	4356	6.28	<0.001
sin:ML.cm:burntTRUE	0.26	0.07	4356	3.89	<0.001

Table S15: Details of the mean daily temperature harmonic model in Glen Tanar. Both R^2 marginal and R^2 conditional were 0.90.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	5.22	0.23	4356	22.33	<0.001
cos	-2.41	0.24	4356	-9.91	<0.001
sin	-4.80	0.22	4356	-21.87	<0.001
ML.cm	0.16	0.05	4356	3.58	<0.001
burntTRUE	1.44	0.21	4356	6.73	<0.001
cos:ML.cm	0.16	0.05	4356	3.21	0.001
sin:ML.cm	0.12	0.04	4356	2.80	0.005
cos:burntTRUE	-0.95	0.25	4356	-3.78	<0.001
sin:burntTRUE	-0.16	0.23	4356	-0.69	0.489
ML.cm:burntTRUE	-0.19	0.04	4356	-4.53	<0.001
cos:ML.cm:burntTRUE	0.04	0.05	4356	0.68	0.497
sin:ML.cm:burntTRUE	-0.09	0.05	4356	-1.90	0.057

Table S16: Details of the daily temperature range harmonic model in Braehead Moss. R^2 marginal was 0.28 and R^2 conditional, 0.43.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	3.77	0.32	5029	11.66	<0.001
cos	-1.62	0.17	5029	-9.52	<0.001
sin	-0.47	0.16	5029	-2.98	0.003
ML.cm	-0.36	0.03	5029	-12.85	<0.001
burntTRUE	-0.57	0.20	5029	-2.87	0.004
cos:ML.cm	0.16	0.03	5029	5.63	<0.001
sin:ML.cm	0.05	0.03	5029	1.75	0.080
cos:burntTRUE	0.51	0.20	5029	2.58	0.010
sin:burntTRUE	-0.07	0.18	5029	-0.40	0.693
ML.cm:burntTRUE	0.24	0.03	5029	7.13	<0.001
cos:ML.cm:burntTRUE	-0.13	0.03	5029	-4.14	<0.001
sin:ML.cm:burntTRUE	-0.05	0.03	5029	-1.77	0.077

Table S17: Details of the mean daily temperature harmonic model in Braehead Moss. R^2 marginal was 0.91 and R^2 conditional, 0.91.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	7.50	0.14	5029	55.21	<0.001
cos	-2.83	0.14	5029	-20.00	<0.001
sin	-4.89	0.13	5029	-36.94	<0.001
ML.cm	0.00	0.02	5029	0.19	0.848
burntTRUE	-0.12	0.14	5029	-0.86	0.389
cos:ML.cm	0.12	0.02	5029	5.29	<0.001
sin:ML.cm	0.03	0.02	5029	1.57	0.116
cos:burntTRUE	0.08	0.16	5029	0.47	0.640
sin:burntTRUE	-0.30	0.15	5029	-2.02	0.044
ML.cm:burntTRUE	0.04	0.02	5029	1.81	0.071
cos:ML.cm:burntTRUE	-0.08	0.03	5029	-3.04	0.002
sin:ML.cm:burntTRUE	-0.02	0.02	5029	-0.87	0.386

6.12. Growing degree hours

Table S18: Details of the linear mixed effects model investigating the effect of the interaction between season ("Se": spring, summer, autumn and winter), and treatment ("Tr": unburnt, no-drought and drought) on daily average growing degree hours at Glen Tanar.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	2.980	0.515	43	5.79	<0.001
Se(Spring)	54.762	6.543	43	8.37	<0.001
Se(Summer)	187.798	3.989	43	47.08	<0.001
Se(Autumn)	163.824	10.970	43	14.93	<0.001
Tr(No-drought)	-1.173	0.697	43	-1.68	0.100
Tr(Drought)	-0.457	0.697	43	-0.65	0.516
Se(Spring) : Tr(No-drought)	22.078	9.253	43	2.39	0.022
Se(Summer) : Tr(No-drought)	44.008	5.978	43	7.36	<0.001
Se(Autumn) : Tr(No-drought)	2.181	15.514	43	0.14	0.889
Se(Spring) : Tr(Drought)	35.005	9.253	43	3.78	<0.001
Se(Summer) : Tr(Drought)	48.123	5.641	43	8.53	<0.001
Se(Autumn) : Tr(Drought)	18.898	15.514	43	1.22	0.230

Table S19: Multiple comparisons of differences in daily growing degree hours between treatment levels within each season at Glen Tanar.

	Estimate	Std. Error	z-value	p-value
winter:nodrought - unburnt	-1.17	0.70	-1.68	0.61
winter:drought - unburnt	-0.46	0.70	-0.65	1.00
winter:drought - nodrought	0.72	0.70	1.03	0.96
spring:nodrought - unburnt	20.90	9.23	2.27	0.22
spring:drought - unburnt	34.55	9.23	3.74	0.00
spring:drought - nodrought	13.64	9.23	1.48	0.76
summer:nodrought - unburnt	42.84	5.94	7.21	0.00
summer:drought - unburnt	47.67	5.60	8.52	0.00
summer:drought - nodrought	4.83	5.94	0.81	0.99
autumn:nodrought - unburnt	1.01	15.50	0.07	1.00
autumn:drought - unburnt	18.44	15.50	1.19	0.91
autumn:drought - nodrought	17.43	15.50	1.12	0.94

Table S20: Details of the linear mixed effects model investigating the effect of the interaction between season ("Se": spring, summer, autumn and winter), and treatment ("Tr": unburnt, no-drought and drought) on daily average growing degree hours at Braehead Moss.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	16.005	1.764	61	9.07	<0.001
Se(Spring)	85.662	4.637	61	18.48	<0.001
Se(Summer)	227.430	4.194	61	54.23	<0.001
Se(Autumn)	189.049	10.087	61	18.74	<0.001
Tr(No-drought)	-4.343	2.115	61	-2.05	0.044
Tr(Drought)	-5.288	2.231	61	-2.37	0.021
Se(Spring) : Tr(No-drought)	3.811	6.509	61	0.59	0.560
Se(Summer) : Tr(No-drought)	13.118	5.878	61	2.23	0.029
Se(Autumn) : Tr(No-drought)	-8.838	14.243	61	-0.62	0.537
Se(Spring) : Tr(Drought)	11.655	6.548	61	1.78	0.080
Se(Summer) : Tr(Drought)	25.001	5.921	61	4.22	<0.001
Se(Autumn) : Tr(Drought)	12.641	14.260	61	0.89	0.379

Table S21: Multiple comparisons of differences in daily growing degree hours between treatment levels within each season at Braehead Moss.

	Estimate	Std. Error	z-value	p-value
winter:nodrought - unburnt	-4.34	2.12	-2.05	0.34
winter:drought - unburnt	-5.29	2.23	-2.37	0.17
winter:drought - nodrought	-0.94	2.12	-0.45	1.00
spring:nodrought - unburnt	-0.53	6.16	-0.09	1.00
spring:drought - unburnt	6.37	6.16	1.03	0.96
spring:drought - nodrought	6.90	6.16	1.12	0.94
summer:nodrought - unburnt	8.77	5.48	1.60	0.68
summer:drought - unburnt	19.71	5.48	3.59	0.00
summer:drought - nodrought	10.94	5.48	1.99	0.38
autumn:nodrought - unburnt	-13.18	14.08	-0.94	0.98
autumn:drought - unburnt	7.35	14.08	0.52	1.00
autumn:drought - nodrought	20.53	14.08	1.46	0.78